doi: 10.14355/papt.2016.04.001

Cutting Mechanism of Drilling CFRP Laminates

Effect of Ultrasonic Torsional Mode Vibration Cutting

Hukuzo Yagishita

Honor Professor, National Institute of Technology, Numazu College, 9-21 Surugadai, Numazu-city, Shizuoka-pref., 410-0015, Japan

yagisita@cy.tnc.ne.jp

Abstract

Cutting mechanism of drilling CFRP laminates and effects of ultrasonic torsional mode vibration cutting are investigated. CFRP laminates are made of carbon fiber reinforced/epoxy-resin matrix composite ply. Challenges in drilling CFRP laminates arise because of anisotropy due to carbon fiber orientation and heterogeneousness between carbon fiber and epoxy-resin. Experimental works are performed to characterize major hole quality parameters and cutting mechanism encountered when conventional drilling CFRP laminates. Some craters of about 100 μm depth are found at the particular position on inner surface of drilled hole and the mechanism for the crater to be generated is revealed based on cutting mechanism of both anisotropic and hheterogeneous composite material. In order to improve hole quality and tool life, the specific drilling assisted by ultrasonic torsional mode vibration of 27 kHz is examined. The ultrasonic torsional mode vibration cutting is considerably effective to restrain the generation of crater and also to elongate tool life about five times.

Keywords

CFRP Laminates; Drilling; Cutting Mechanism; Anisotropy; Heterogeneousness; Hole Quality; Ultrasonic Torsional Mode Vibration Cutting; Tool Life

Introduction

Wide spread applications of composite material have been significantly growing in aerospace, naval, space and automotive industries. Especially, CFRP (carbon fiber reinforced plastics) laminates have a higher strength/weight ratio (about ten times larger tensile strength than advanced aluminum alloy in spite of about one half specific gravity) and high heat resistance. Therefore, recently most of wing, tail assembly and body of aircraft have been manufactured by assembling several parts made of CFRP laminates. Bolting and riveting are currently the preferred methods for fastening composite skins to the metal or other composite parts in assembly of aerospace and automotive composite structures. Namely, drilling of CFRP laminates is indispensable for manufacturing aircraft and automotive composite structure and the quality of drilled holes strongly affects the fatigue strength of the structure besides the reliability of aircraft.

The particular objective of the present work is to conduct drilling experiments of CFRP laminates to investigate the cutting mechanism and the effects of ultrasonic torsional mode vibration cutting. Experimental work is performed to characterize major hole quality parameter and cutting mechanism encountered when drilling CFRP laminates and also to examine specific drilling assisted by ultrasonic torsional mode vibration cutting. Inner surface texture of drilled hole and tool life are investigated and discussed by comparing the results of conventional drilling with those of specific drilling assisted by ultrasonic torsional mode vibration cutting.

Experimental Setup and Procedure

Material Systems

CFRP is made from combining carbon fiber clusters with epoxy-resin matrix, to create a strong, high temperature composite. A workpiece shown in Fig.1 is CFRP laminates which is made of 11 ply of carbon fiber oriented as follows; 0^0, 90^0, 0^0, 90^0, 0^0, 90^0, 0^0, 90^0, 0^0, 90^0, 0^0, and the skin two plies are thinner than 0.3 mm thickness of mid 7 plies. The workpiece is consolidated from laminates of 11 prepregs including one oriented fiber cluster using the autoclave method.

Experimental Method and Procedures in Drilling

Drilling experimental setup assisted by ultrasonic torsional mode vibration consists of vibration unit, oscillation unit and display unit as shown in Fig.2.

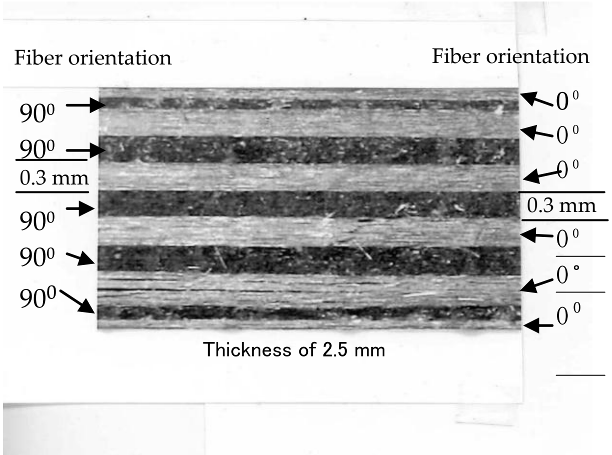


FIG. 1 SECTIONED VIEW OF WORKPIECE

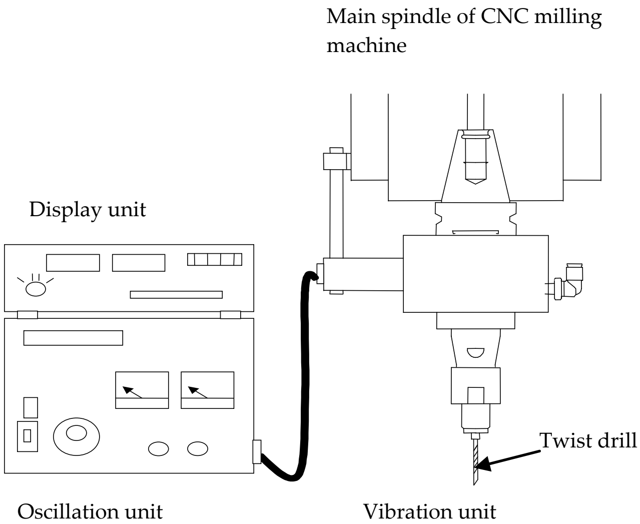


FIG. 2 SCHEMATIC DRILLING EXPERIMENTAL SETUP ASSISTED BY ULTRASONIC TORSIONAL MODE VIBRATION

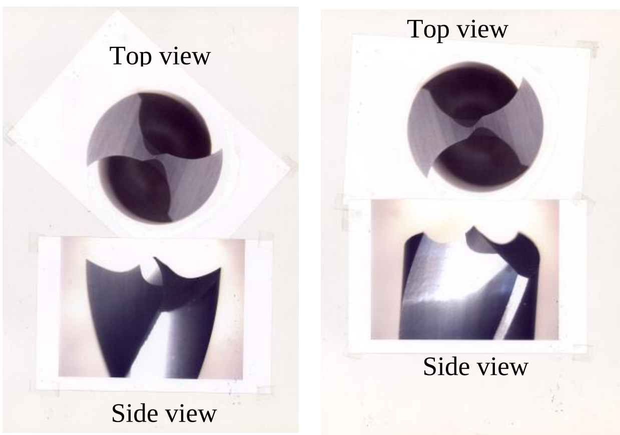


FIG.3 APPEARANCE OF ViO COATED CEMENTED CARBIDE FIBER DRILL USED (ϕ3 mm)

The taper shank of vibration unit is attached rigidly to the main spindle of CNC milling machine. The electric control signal from oscillation unit oscillates torsionally at 27 kHz, the twist drill attached to the end of vibration unit, which are rotating as one body with the main spindle of the milling machine. Display unit expresses resonant

frequency, tip amplitude of twist drill constantly, and which one of supplied voltage, ampere or electric power is selectively expressed on the display during running of the drilling system.

ViO coated cemented carbide fiber drill of 3 mm diameter which have a pair of sepecial cutting edge shown in Fig.3, are used for all experiments. As shown in Fig.3, thinning is applied to the chisel edge and margin does not exist being different from a conventional twist drill. The summary of drilling conditions for CFRP laminates is listed in Table 1.

TATABLE 1 THE SUMMARY OF DRILLING CONDITIONS FOR CFRP LAMINATES

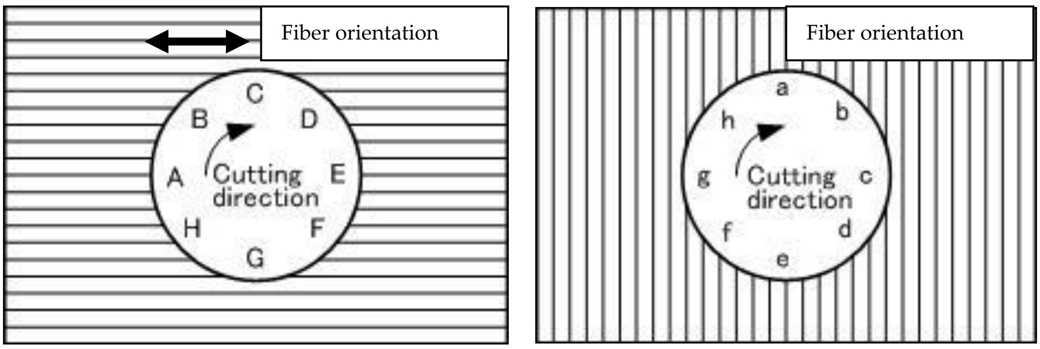
Drilling of CFRP laminates	
Machine tool	Vertical milling machine with CNC control
Workpiece material / Shape	CFRP laminates of 11 ply / Plate of 2.5mm thickness
Tools / Diameter / Length	ViO coated cemented carbide fiber drill / ϕ3mm in diameter / 36 mm in length
Drilling conditions (Dry cutting)	Rotational speed 1480rpm (Cutting speed 13.9m/min)
	Feed 0.04 mm/rev (Feed rate 59.2 mm/min)
Ultrasonic torsional mode vibration	Frequency 27 kHz Amplitude 12.5 μm Maximum vibrational speed 127 m/min Maximum power 50 w

Results and Discussion

Cutting Mechanism

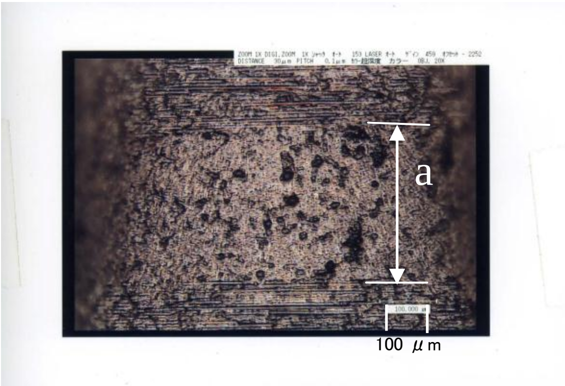
The variation of relative angle between fiber orientation and cutting direction is shown in Figs.4(a) and (b). (a) and (b) in Fig. 4 show the ply of fiber orientation 0^0 and 90^0 respectively. In these figures, the relative angle at A, E in (a) and a, e in (b) is 90^0, and the angle at C, G and c, g is 0^0, and the angle at B, F and b, f is -45^0, and the angle at D, H and d, h is $+45^0$ respectively. Inner surface textures of hole, which are observed using a laser beam scanning microscope, at relative angle of 90^0, 0^0 and $\pm45^0$ are shown in Figs.5(a), (b) and (c). (a) in Fig.5 at relative angle of 90^0 shows the almost smooth surface but several dark dots are seen. On the other hand, (b) in Fig.5 at relative angle of 0^0 shows a lot of scratched traces caused by rubbing of cutting edges having the length of more than 400μm. In (c) of Fig.5 at relative angle of $\pm45^0$, two dark areas are seen at D of the angle $+45^0$.

It is confirmed that the dark areas form craters of about 100μm depth by more detaied observation.

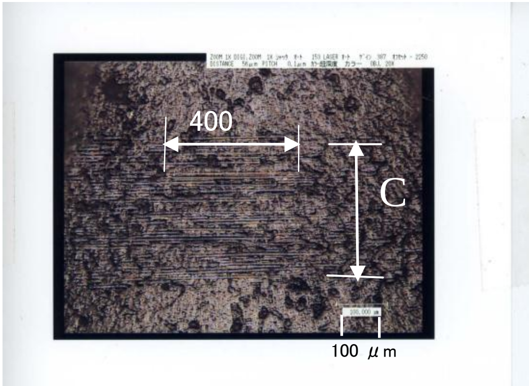


(A) PLY OF FIBER ORIENTATION 0^0 (B) PLY OF FIBER ORIENTATION 90^0

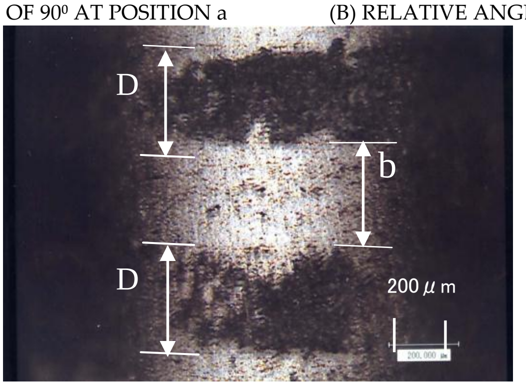
FIG.4 RELATIVE ANGLE BETWEEN FIBER ORIENTATION AND CUTTING DIRECTION



(A) RELATIVE ANGLE OF 90^0 AT POSITION a



(B) RELATIVE ANGLE OF 0^0 AT POSITION C



(C) RELATIVE ANGLE OF $+45^0$ AT POSITION D AND - 45^0 AT POSITION b.

FIG.5 INNER SURFACE TEXTURE AT RELATIVE ANGLE OF 90°, 0° AND ±45°

Chip Formation

During drilling of feed 0.04 mm/rev, which is about one eighth of ply thickness 0.3 mm, typical two types of chip formation Ⅰ, Ⅱ, and rare types of Ⅲ, Ⅳare generated as shown in Fig. 7. Type Ⅰ (dust type) is most of all chips, and Type Ⅱ (continuous type) is small number of chips. In rare Type Ⅲ, a lot of scratched traces and adhesion of dark lump are seen. Type Ⅳ is dark lump similar to adhesion in Type Ⅲ.

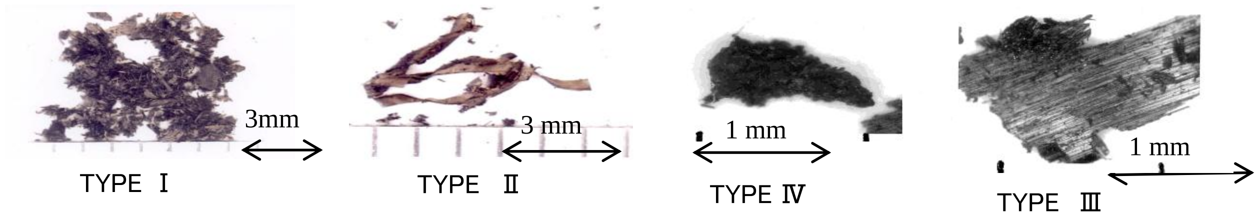
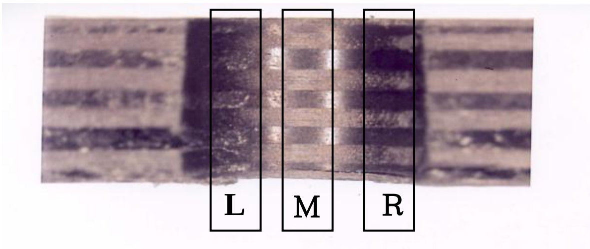


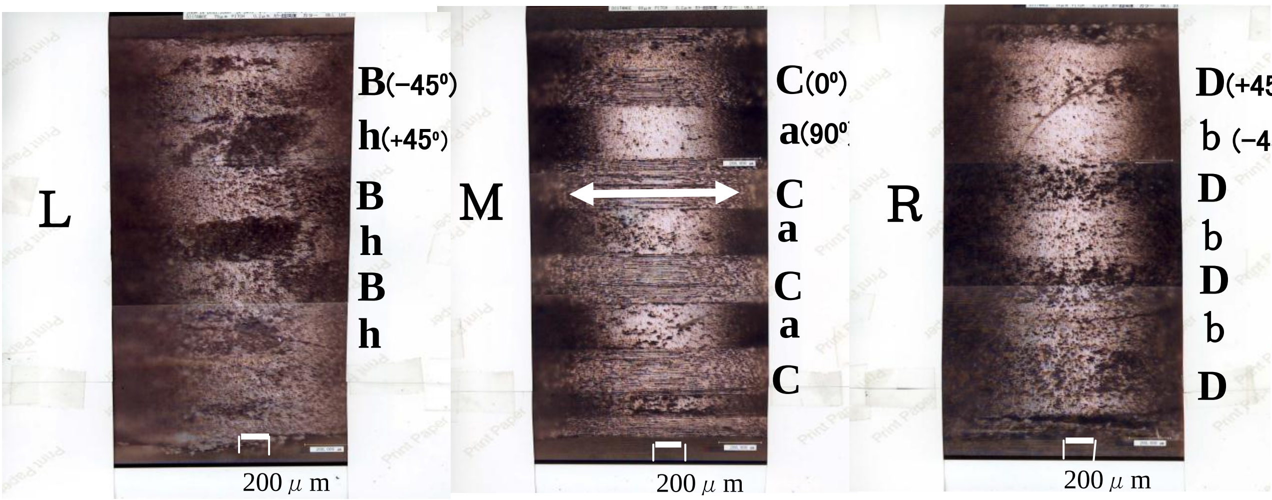
FIG.6 FOUR TYPES OF CHIP FORMATION

Assessment of Hole Quality

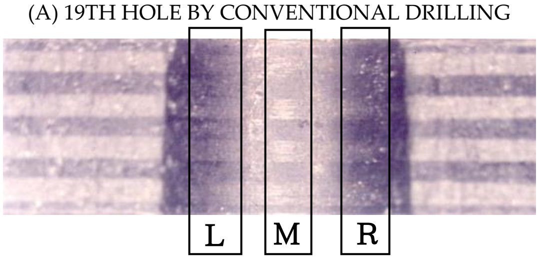
Assessment of hole quality consists of hole diameter and roundness, inner surface texture, and inlet and outlet delamination of drilled hole. The present work especially focuses the subject on inner surface texture and hole diameter.

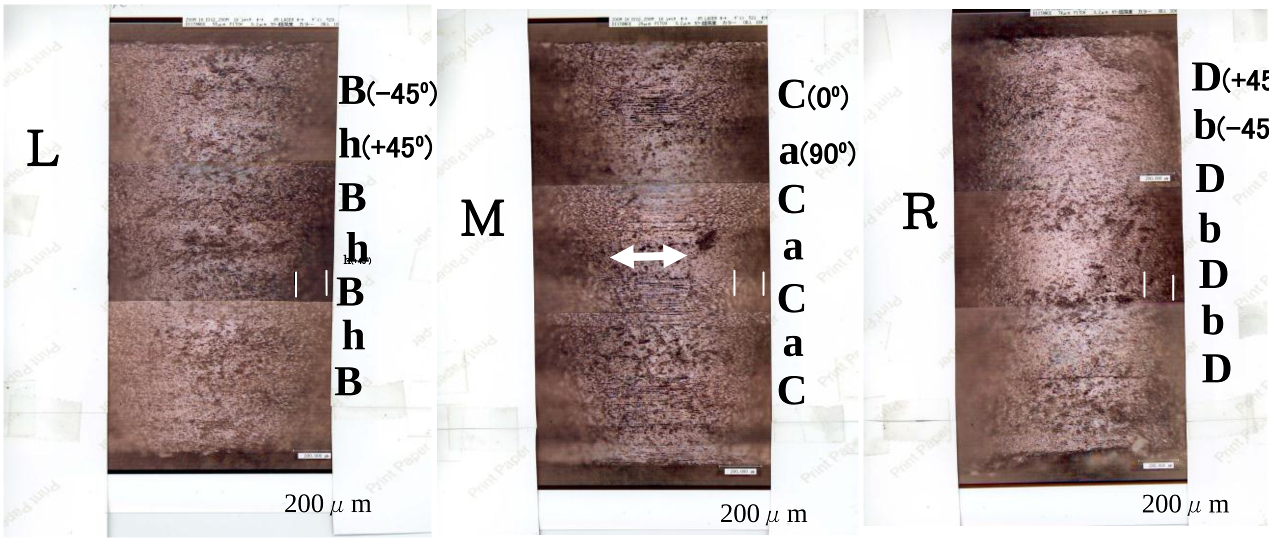
1) ***Effects of Ultrasonic Torsinaal Mode Vibration Cutting on Inner Surface Texture***





(A) 19TH HOLE BY CONVENTIONAL DRILLING





(B) 19TH HOLE ASSISTED BY ULTRASONIC TORSIONAL MODE VIBRATION CUTTING

FIG.7 COMPARISON BETWEEN INNER SURFACE TEXTURE OF 19TH HOLE BY CONVENTIONAL DRILLING AND THAT ASSISTED BY ULTRASONIC TORSIONAL MODE VIBRATION CUTTING

To examine the effect of ultrasonic torsional mode vibration cutting on the inner surface texture of drilled hole, the inner surface is observed using a laser beam scanning microscope after being cut at the center line of hole with an abrasive water jet cutting. Figures 7 (a) and (b) show the inner surface texture of half hole at 19th hole by conventional drilling and that by specific drilling assisted by ultrasonic torsional mode vibration cutting. In Fig. 7 (a), at the specific position of h and D (relative angle of $+45^0$) following to g and C having wide scratched traces ⇔ shown in M of Fig.7(a), the dark areas are found. From the similar observations for the opposite half inner surface of the hole in Fig.7(a) though the figure is omitted, the dark areas are found at the position of d and H. By more detailed observation, it is ascertained that the dark areas form craters of about 100 μm depth. However, in Fig.7(b) assisted by ultrasonic torsional mode vibration cutting, the craters are not seen at all at the same positions of h and D as those in Fig.7(a).

2) *Mechanism for Craters to be Generated*

The mechanism for craters to be generated at only the relative angle of +45^0 for conventional drilling is considered as follows. Comparing the surface texture at the position C of relative angle 0^0 in Fig. 7(a) with the same that in Fig. 7(b), we can find that the width of scratched traces of cutting edges is clearly different as shown by the white arrow ⇔ in the Figures M of Fig. 7(a) and (b). Namely, in the case of Fig. 7(b) assisted by ultrasonic torsional mode vibration cutting, since instantaneous cutting is repeated 27000 times during one second (27kHz), the ability for cutting edge to cut carbon fiber cluster would be considerably improved. As a result, the width of scratched traces caused by rubbing of cutting edges against carbon fiber cluster is narrowed. Since shortening of the rubbing duration contributes to decrease heat generated by friction, the temperature of cutting area is restrained. As shown in Table 2, the coefficient of thermal conductivity of epoxy-resin is about one hundredth smaller than that of carbon fiber and also the carbon fiber cluster has better thermal conductivity in the fiber orientation than that in the other direction.

TABLE 2 COMPARISON OF COEFFICIENT OF THERMAL CONDUCTIVITY

Material	Coefficient of thermal conductivity [cal/㎝･s･℃]
Carbon fiber	5.7×10^{-2}
Epoxy-resin	$4\sim5\times10^{-4}$

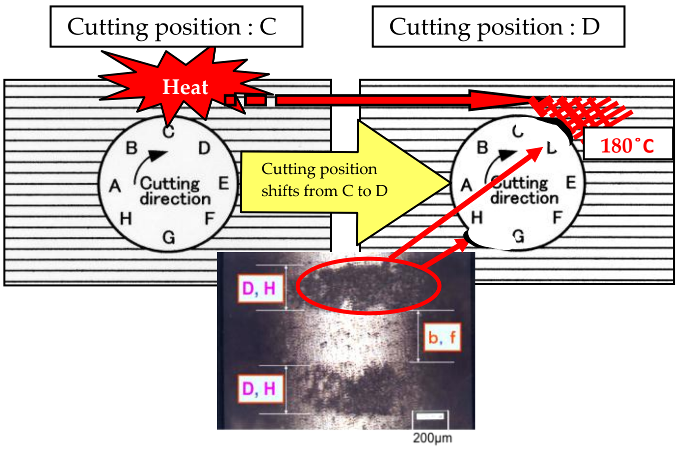
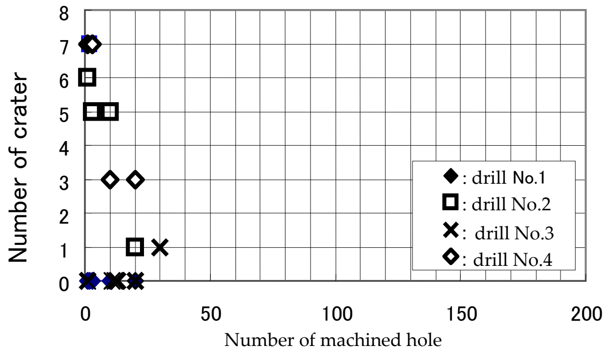


FIG.8 MEVCHANISM FOR CRATERS TO BE GENARATED

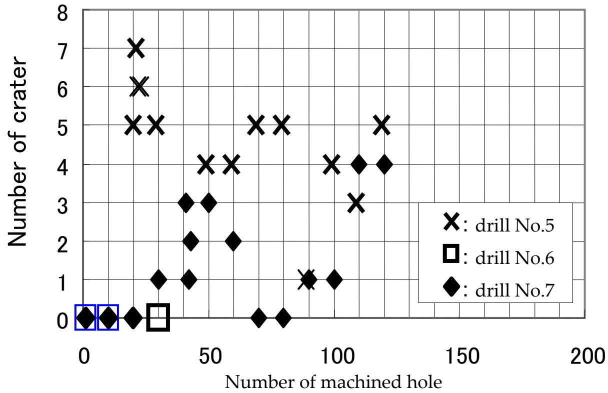
As shown in Fig. 8, the heat generated by rubbing at position C is conducted to the following position D through carbon fiber cluster and the temperature of the area near position D would rise. It is well-known that epoxy-resin becomes suddenly brittle at the temperature over about 180℃ of its glass transition temperature. When the cutting edge of drill comes to the position D after the temperature of position D became the glass transition temperature, the epoxy-resin near position D would be dropped out. As a result, the crater would be generated. Therefore, the crater would be also generated at position H opposite to position D. Chip Type Ⅳ shown in Fig. 6 must be a lump dropped out when a crater was generated. From the above-mentioned consideration, it can be understood that craters are generated only at the positions h, D, d and H of the relative angle +45°.

3) *Effect of Ultrasonic Torsional Mode Vibration Cutting on Generation of Crater*

Figures 9 (a) and (b) show the relationship between number of crater, which are found on the inner surface of half hole, and number of machined hole. (a) in Fig.9 is the relationship by conventional drilling and (b) in Fig.9 is that by specific drilling assisted by ultrasonic torsional mode vibration cutting, respectively. In (a) of Fig. 9, the crater is generated from first hole during conventional drilling, however, in (b) of Fig.9 it is generated after 20th or 30th hole drilling during specific drilling assisted by ultrasonic torsional mode vibration cutting. This can be understood that the assistance of ultrasonic torsinal mode vibration in drilling is effective to restrain the rise of cutting temperature because of intermittent cutting of 27 kHz and as a result the occurance of crater is delayed after 20th or 30th hole drilling.



(A) CONVENTIONAL DRILLING

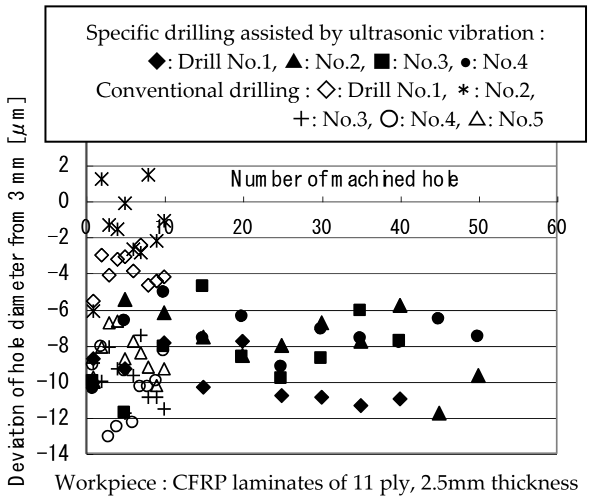


(B) SPECIFIC DRILLING ASSISTED BY ULTRASONIC TORSINAL MODE VIBRATION CUTTING

FIG.9 RELATIONSHIP BETWEEN NUMBER OF CRATER ON HALF HOLE AND NUMBER OF MACHINED HOLE

4) *Effect of Ultrasonic Torsional Mode Vibration Cutting on Hole Diameter*

Figure 10 shows the relationship between deviation of hole diameter from 3 mm and number of machined hole. As shown in Fig. 10, it is seen that scattering of deviation of hole diameter from 3 mm can be reduced from 16 μm to 8 μm by assistance of ultrasonic orsional mode vibration cutting. The large scattering of hole diameter by conventional drilling would be induced by the occurrence of crater on the inner surface of hole.



Workpiece : CFRP laminates of 11 ply, 2.5mm thickness
Diameter of drill : ϕ3 mm, Length of drill : 46 mm
Amplitude of vibration : 22.5 μm
(Max. vibrational Speed of 229m/min)
Rotational speed of drill : 2200 rpm (20.7 m/min)
Other conditions are the same as those in Table 1.

FIG.10 RELATIONSHIP BETWEEN DEVIATION OF HOLE DIAMETER FROM 3mm AND NUMBER OF MACINED HOLE

5) Effect of Ultrasonic Torsional Mode Vibration Cutting on Tool Life

Based on the criteria of tool life when the wear width of circumferential cutting edge reaches to 0.07mm, effect of ultrasonic torsional mode vibration cutting on tool life of drill was examined. Since tool life is affected by the occurrence of micro-chipping, drilling tests were executed five times in conventional drilling and also in specific one assisted by ultrasonic torsional mode vibration cutting respectively. As shown in Fig. 11, the assistance of ultrasonic torsional mode vibration to drilling CFRP laminates is significantly effective to extend the tool life. It can be understood thoroughly that the extension of tool life is caused by for temperature rise to be restrained at cutting edge due to decrease of rubbing duration between cutting edge and carbon fiber cluster at the position C of relative angle 0˚ shown in Fig. 7(b).

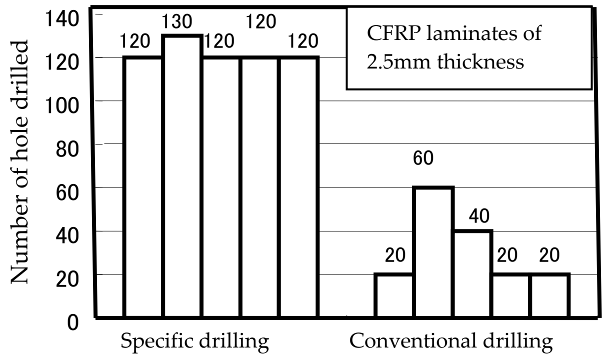


FIG.11 COMPARISON OF TOOL LIFE BETWEEN CONVENTIONAL DRILLING AND SPECIFIC ONE

Conclusions

The cutting mechanism of CFRP laminates is investigated for drilling and also the effect of ultrasonic torsional mode vibration cutting on the drilling is examined. The results revealed in this study show that the relative angle between fiber orientation and cutting direction of cutting edge, and also the heterogeneousness between carbon fiber and epoxy-resin play significant roles in drilling of CFRP laminates. The assistance of ultrasonic torsional mode vibration cutting is considerably effective to improve inner surface texture of hole and tool life. The conclusions are summarized as follows;

1) At the position of relative angle 0^0 between fiber orientation and cutting direction, cutting edges of drill rub severely carbon fiber cluster and the rubbing leaves scratched traces on the inner surface of hole and simultaneously generates frictional heat.

2) At the position of relative angle $+45^0$ following to that of relative angle 0^0, the crater of about 100μm depth, which is observed as dark area by a microscope, is generated from first hole drilling.

3) It is revealed that the mechanism for the crater to be generated on the inner surface of hole is induced by both anisotropy due to carbon fiber orientation and heterogeneousness between carbon fiber and epoxy-resin.

4) By assistance of ultrasonic torsional mode vibration cutting, the occurrence of crater is restrained after 20th or 30th hole drilling, and tool life of drill is elongated by five times of that of conventional drilling in the experiments at this time.

5) It is presumed that restraining the occurrence of the crater and elongating tool life of drill would be induced by reduction of frictional heat generation due to shortening of rubbing duration between cutting edges and carbon fiber clusters.

REFERENCES

[1] Bennett, B.A. "Carbon-fiber composite: A light-weight alternative." Mechanical Engineering, Vol.95, No.3, p.34, 1985.

[2] Watkins, J. "Aerospace Manufacturing—Materials: New Rules, NEW GAME." Mechanical Engineering, Vol.132, No.3, pp.75-86, 2004.

[3] Waurzyniak, P. “Aerosspace Manufacturing－Lean FIGHTER.” Mechanical Engineering, Vol.134, No.3, pp.121-132. 2005.

[4] Hogan, B. J. “Aerospace Manufacturing－Automation Speed A380 Wing Assembly.” Mechanical Engineering, Vol.134, No.3, pp.121-132, 2005.

[5] Kim, D., Ramulu, M., Pederson, W. “Machinability of Titanium/Graphite Hybrid Composites in Drilling.” Transactions of NAMRI/SME, Vol.33, pp.445-452, 2005.

[6] Kumabe, J. “Vibration Cutting for Precision Machining－The Fundamental and Applications－(in Japanese).”, Jikkyo Publish Co., Ltd., Tokyo, 1979.

[7] Kumabe, J. “Study on Precision Vibration Pulse Plaining (in Japanese).” Journal of JSPE, Vol.42, No.11, pp.1036-1042, 1976.

[8] Kumabe, J., Saito, T. and Tanaka, M. “Super Precision Ultrasonic Vibration Turning (in Japanese).” Jounal of JSPE, Vol.47, No.10, pp.1252-1257, 1981.

[9] Suzuki, H., Yagishita, H. “Burrless Drilling by Vibration Cutting Applying Ultrasonic Torsinal Mode Vibration.” Transactions of NAMRI/SME, Vol.33, pp.461-468, 2005.

[10] Yagishita, H. “Cutting Mechanism of Drilling CFRP Laminates and Effect of Ultrasonic Torsional Mode Vibration Cutting.” Transactions of NAMRI/SME, Vol.34, pp.213-220, 2006.

[11] Yagishita, H. “Effect of Ultrasonic Torsional Mode Vibration Cutting on Drilling in CFRP Laminates.” Proceedings of ASPE Spring Topical Meeting on Vibration Assisted Machining Technology, pp.92-97, April 2007.

Appendixes

The mechanism for the crater to be generated on the inner surface of drilled hole, which is proposed by the author, is shown by means of following evidence.

Figure A1 shows the sectioned view of CFRP laminates of 34 ply and 12 mm thickness. In Fig. A1 upper and lower skin ply is woven. In sandwiched 6 ply, 6 ply, 11 ply, 6 ply and 3 ply from down to up, each ply contains straight cabon fiber cluster respectively and the thickness of each ply is 0.3 mm same to the white color ply shown in Fig. A1. The white color ply contains carbon fiber cluster parallel orientation to this paper surface. The orientation of carbon fiber cluster contained in the other ply is not known by Fig. A1.

Figures A2 (a) and (b) show inner surface texture of drilled hole and roundness curve after a hole of 6 mm diameter is drilled to the CFRP laminates shown in Fig.A1. In Fig. A2 (a), several craters on each ply are seen clearly of which the position is shifted regularly in axial direction. Moreover, in Fig. A2(b), two craters are seen clearly at the opposite position in roundness curve. The fact that crater’s position is shifted in axial direction in Fig.A2(a) means that the orientation of carbon fiber cluster cotained in each ply is shfted.

Figure A2 (a) and (b) evidences that the mechanism for the crater to be generated on inner surface of hole proposed by the author is true.

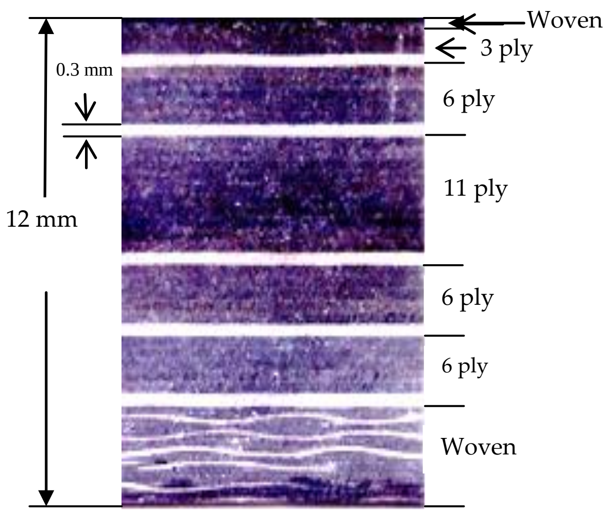
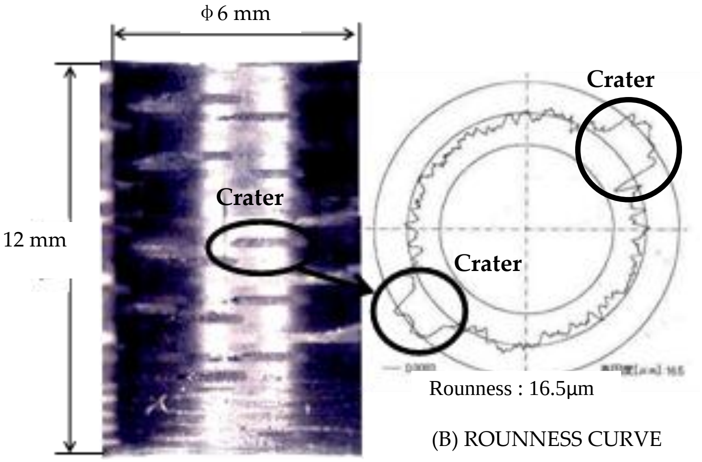


FIG.A1 SECTONED VIEW OF CFRP LAMINATES (34 plys, 12 mm thickness)



(B) ROUNNESS CURVE

(A) INNER SURFACE TEXTURE OF DRILLED HOLE

Drilling conditions:
ViO coated cemented carbide drill: ϕ6 mm
Rotational speed: 630 rpm (Cutting speed: 11.9 m/min)
Feed rate: 12.6 mm/min (Feed: 0.02 mm/rev)
Dry cutting

FIG.A2 INNER SURFACE TEXTURE OF DRILLED HOLE AND ROUNDNESS CURVE